

DARK MATTER – PERSONAL VIEW

Bohdan Paczyński
Princeton University Observatory, Princeton, NJ 08544-1001
bp@astro.princeton.edu

ABSTRACT

Traditional evidence for large amount of dark matter is based on dynamical consideration for systems with $t_{dyn} \gg t_{obs}$. Recent observational and theoretical developments in gravitational lensing offer a much more robust determination of the mass distribution in some galaxies and their clusters, with the precision comparable to that obtainable for double stars for which $t_{dyn} < t_{obs}$, and offer independent and direct evidence for the presence of dark matter.

Gravitational microlensing and femtolensing offer a possibility to detect MACHOs with masses in excess of $\sim 10^{-15} M_{\odot}$. The recent detections of microlensing events by the EROS, MACHO and OGLE teams do not require any dark lenses as ordinary low mass stars are compatible with the observations. However, these searches will soon either detect genuine MACHOs, or they will place stringent upper limits on their number density.

1. INTRODUCTION

The presence of dark matter is inferred through its gravitational effect on the luminous matter. The same basic concept led John C. Adams and Urbain Le Verrier to the prediction of the existence of a dark object which was responsible, through its gravity, for the perturbations of the orbit of Uranus. The object was discovered by Johann Galle in 1946, and was named Neptune. More recently accurate masses of the dark matter binary system PSR 1913+16 were determined on the basis of dynamical considerations (Taylor & Weisberg 1989, and references therein). For Neptune and for PSR 1913+16 the mass to light ratio (M/L) is enormous, much higher than for any galaxy or a cluster of galaxies. Presumably, these two types of dark objects, and their M/L, are not typical for the universe at large.

Less precise dynamical consideration are the basis for the claim that there is plenty of dark matter in clusters of galaxies (Zwicky 1933) as well as in galaxies (Oort 1932, Freeman 1970). The propagation of light from distant sources is a very powerful tracer of mass distribution through the phenomenon called gravitational lensing.

Various inferences have a different degree of reliability. My personal rating of the various methods is as follows:

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| 1) dynamical, with $t_{dyn} < t_{obs}$ | – the best |
| 2) gravitational lensing | – good |
| 3) dynamical, with $t_{dyn} > t_{obs}$ | – fair |
| 4) mass to light ratio | – poor |
| 5) cosmological principles | – meaningless |

where t_{dyn} is the dynamical time scale for the system, like the binary period, or the virialization time, and t_{obs} is the length of time over which the observations

were carried out.

There is no doubt that the first technique provides a very robust mass measurements. This is the only truly fundamental method of measuring masses in astronomy. In practice it is applicable only to binary stars and to planets. The third method, with $t_{dyn} > t_{obs}$, or rather $t_{dyn} \gg t_{obs}$, is by far the most commonly used in modern inferences for the presence of dark matter. Its reliability varies a lot from case to case. The second method, which only recently developed to the extent that it is practical under a range of conditions, is the main one to be discussed in this review. It is very direct, using light rays as tracers of space-time geometry, and it does not require the mass distribution to be in any kind of equilibrium. Its main practical weakness is that in most cases the model of mass distribution is not unique. Fortunately, there are many cases in which models are reasonably accurate, and the observational as well as modeling techniques are developing rapidly.

The last two methods are far less reliable. For some astronomical object, be it a galaxy or a cluster of galaxies, the mass is estimated with the method (3). The luminosity of the system is measured directly, and the M/L is calculated. The estimates of M/L are available for many galaxies, groups and clusters of galaxies, and some average (median?) value of M/L is guessed to be representative for the whole universe. This value being of the order of $\sim 300 M_{\odot}/L_{\odot}$ implies that most matter in the universe is dark.

It is important to remember that we have no fundamental theory that would allow us to calculate the efficiency of star formation from diffuse gas or the stellar mass function. It is not known how the efficiency of star formation and the shape of the mass function depend on the initial gas pressure, magnetic fields, chemical composition, ambient radiation field, local energy density in cosmic rays, etc. Our knowledge in this field is empirical only, and even this is incomplete and often unreliable. Therefore, my personal rating of the estimates of the amount of dark matter in the universe as based on the method (4) is ‘poor’.

My personal rating of the method (5) is ‘meaningless’ even though there is a strong theoretical bias towards cosmology with $\Omega = 1$. The common justification for this bias comes from the theory of inflation, which in its original form ‘predicted’ $\Omega = 1$. However, the modern theory of inflation can accommodate almost anything: certainly $\Omega = 0.3$ (Kamionkowski et al. 1994, Bucher et al. 1994), and a ‘tilted’ (i.e. non-Zeldovich) spectrum of primordial perturbations (Adams et al. 1992) are among the many ‘predictions’. Therefore, even though the inflation remains a wonderful concept, and even though in some distant future it may become rigorous, it currently provides no realistic estimate for the amount of dark matter. It is listed as a method number 5 for historical reasons only.

There is no hope to use method (1) on cosmological scale, as typically we may have $t_{dyn} \sim 10^8$ years, or even more, orders of magnitude above t_{obs} . Hence the method (3) is by far the most common. However, just as on the stellar scale the method (1) is the bedrock of all secondary methods, so the method (2) should become the bedrock for mass estimates on the galactic scale, even though its range of applicability is rather limited so far. There are many excellent recent reviews and books on gravitational lensing: Blandford & Narayan (1992), Refsdal & Surdej (1994), Schneider, Ehlers, & Falco (1992), Surdej et al. (1993). As all important references can be found in these reviews, and the page limit imposed on this paper is very strict, I make no attempt to provide a complete or even fair reference to all important contributions to this rapidly growing field,

and I apologize for any discomfort this may create.

2. GRAVITATIONAL MACROLENSING

Strong gravitational lensing makes multiple images of a single source. If the separation between the images is large enough (arcseconds in optical domain, milli arcseconds in the radio) so that they can be seen separately, the phenomenon is referred to as macrolensing. The gravitational lensing is called weak if only one distorted image of a source is present.

The largest scale on which the strong gravitational lensing was detected and on which robust quantitative models of the lens mass distribution are available are clusters of galaxies, in which ‘luminous arcs’ were discovered a few years ago (Lynds & Petrosian 1989, and references therein). Later, less spectacular but much more common ‘arclets’ were found in many clusters. These are caused by the weak gravitational lensing and are so numerous that they proved to be very useful for the studies of mass distribution (Tyson et al. 1990, and references therein). The ‘arcs’ and the ‘arclets’ are the highly distorted images of galaxies which are at a larger redshift than the cluster itself, and so they are easily recognized being much bluer than the cluster galaxies.

The models of cluster mass distributions will be discussed later during this symposium, so I would like to point out only a few obvious results. First, the ‘arcs’ demonstrate that the density of matter increases strongly towards cluster centers and exceed the critical value needed for strong gravitational lensing. In other words the core radii of the mass distribution are much smaller than believed only a decade ago. Second, the column mass density within a cluster can be measured with the lensing model while the surface brightness can be measured directly. Hence, the value of M/L can be determined with a fairly high accuracy.

Many gravitational lenses are caused by galaxies, which form a double or a quadruple image of a distant quasar. The total mass contained between the images can be measured with a very high precision (Kochanek 1991), and so can be the light of the lensing galaxy, thereby allowing a precise M/L estimate to be made. In some cases a model gives a column mass density along the lines of sight towards the individual images (cf. Kochanek 1994).

An interesting case is the double quasar 0957+561 (Walsh et al. 1979), which has a VLBI radio jet some 40 milli arcseconds long. Two different images of the jet are observed. The matter along the two lines of sight is mostly dark and the microlensing properties are different. Therefore, a detailed comparison of the two radio images offers an opportunity to either detect the presence of $\sim 10^6 M_\odot$ compact objects (black holes? dark clusters?) or demonstrate that such objects do not exist (Wambsganss & Paczyński 1992, Garrett et al. 1994).

3. GRAVITATIONAL MICROLENSING

A lensing galaxy is made of stars and some dark matter. We know nothing about the form of dark matter, but the stars can be treated as point masses. Each image of a lensed quasar is seen through the lensing galaxy, and in turn is lensed by the stars close to the line of sight, which split each image into a number of sub-images. The sub-images are so close to each other that they cannot be seen separately and the phenomenon is called gravitational microlensing. It can be detected because the relative motion of the lens, the source, and the observer,

or the motions within the lens make the combined intensity of all micro-images vary. There are two extreme types of microlensing, corresponding to a very low and large ‘optical depth’, respectively. In the very low optical depth limit there is either no, or at most one star close to the line of sight, and there are either one or just two bright micro-images. In case of a large optical depth there are many stars close to the line of sight and many bright micro-images are formed. The properties of lensing in these two regimes are very different.

The optical depth to gravitational microlensing is very low when we look at the stars in our galaxy, or at the stars in the Magellanic Clouds. Along the lines of sight towards these stars there may be other stars, brown dwarfs, planets and black holes acting as gravitational microlenses. The probability that the brightness of a star is magnified by more than ~ 0.3 mag is very low, $\sim (V_{rot}/c)^2 \sim 10^{-6}$, where V_{rot} is the rotational velocity of our galaxy (Paczynski 1986, 1991, Griest 1991, Griest et al. 1991). Three groups are conducting the search for such events: EROS, MACHO, and OGLE, and all three reported the detection of candidate events towards the LMC and/or the galactic bulge (Alcock et al. 1993, 1995, Aubourg et al. 1993, Udalski et al. 1993, Udalski et al. 1994a, 1994b, 1994c, Bennett 1994).

This is a field at its infancy, but some reasonably firm conclusions are already available. First, it has been demonstrated that it is possible to detect the very rare events of gravitational microlensing at a rate of a few per year (OGLE) or even a few dozens per year (MACHO). Second, it is possible to detect the events in real time with the OGLE ‘early warning system’ EWS (Paczynski 1994a, Udalski et al. 1994c), and with the MACHO ‘alert system’ (Bennett et al. 1994). This is important, as the follow-up observations are possible while the event unfolds. Third, the rate of events towards the galactic bulge turned out to be higher than expected by a factor of 2-4, indicating that our understanding of the galactic structure is inadequate. It follows, that microlensing offers a new way to study the galactic structure. Four, even though the search for microlensing events was undertaken with the dark matter in mind, the results available so far neither prove nor disprove the hypothesis that dark matter is made of massive compact objects (MACHOs). All events detected so far are compatible (within observational and theoretical errors) with the lenses being ordinary stars. My personal conclusion is that MACHOs, if they exist, will be detected within the next few years.

There is one major misconception which invalidates many theoretical studies: the incompleteness of our knowledge about the galactic structure means that currently there is no meaningful way to relate the observed time scales of microlensing events to the lens masses, as it is not clear if the lenses detected towards the galactic bulge are in the galactic disk (Alcock et al. 1995), or are they in the galactic bar (Paczynski et al. 1994), while the lenses detected towards the LMC may be in the disk or the halo of our galaxy, or they may be in the bulge or the halo of LMC. The inferences about the lens masses will become realistic when the location of lenses is established with the future observations.

There are also misconceptions about the statistical properties expected of microlensing events. As the events are so rare it is commonly believed that they should not repeat. In fact we do know that the stars are commonly double, and the same presumably holds for the lenses. Mao & Paczynski (1991) estimated that $\sim 10\%$ of all events may have a strong signature of a double lens. Indeed, in a small sample of 13 events detected by the OGLE there is one very dramatic case of a double lens, the OGLE #7 (Udalski et al. 1994d, Bennett et al. 1994), in which the two lensing stars were separated by approximately one Einstein ring

radius. Another possible OGLE double lens was analyzed by Mao & DiStefano (1995). The distribution of binary separations is uniform in the logarithm of separation. Therefore, there should also be sources microlensed by the two components of a binary with the separation exceeding the Einstein ring radius. In this case there should be two separate single microlensing events, separated by a few months or a few years. A similar dual event might be observed if the source is double (Griest 1992, Griest & Hu 1993). I roughly estimate that a few percent of all events should be like that, i.e. they should repeat. If such repeating cases are not found then either binary stars are less common than we think, or the detection criteria discriminate against them.

A very different regime of microlensing and a very different type of variability is expected when the optical depth is modest or even large. This is the case of a quasar lensed by a galaxy at a cosmological distance. The first clear case of such microlensing was reported for 2237+0305, i.e. Huchra's lens (Huchra et al. 1985, Irwin et al. 1989). The most dramatic event was reported by Pen et al. (1994): the luminosity of one of the four quasar images increased by 1.5 mag during a time interval of ~ 2 months, and declined by the same amount during a few days. This is compatible with a theoretical picture in which the magnification pattern is a maze of caustics produced by the stars randomly distributed in the lensing galaxy (Wambsganss et al. 1990). The most common light variation is caused by the source (the quasar) crossing one of the many caustics. The variation on one side is relatively slow, with the time scale proportional to the square root of a typical stellar mass. The variation on the other side would be instantaneous for a point source, and has a finite rate for an extended source, with the duration proportional to the source size. Still, there is a surprise in the Pen et al. (1994) result: it implies the quasar is as small as $\sim 10^{14}$ cm in the continuum light, much smaller than expected in the conventional accretion disk models (Rauch & Blandford 1991, Jaroszyński et al. 1992).

There are also misconceptions about the microlensing in the large optical depth regime. Contrary to common belief it is not possible to relate the observed light variation to a specific stars, as the caustics are formed by many stars acting together, gravity being a long range force. Also, the relation between the time scale of the light variability and the microlens masses has not been worked out in any paper published so far. Even though the time scale has to be proportional to a square root of some average microlens mass, the dimensionless coefficient of proportionality is not the same as it is in the optically thin case. Therefore, it is not possible (at this time) to estimate the microlens masses in the Huchra's lens to better than an order of magnitude.

4. GRAVITATIONAL FEMTOLENSING

Gravitational microlensing, as well as macrolensing, operates within the approximation of geometrical optics. Yet, under certain conditions the diffraction effects might be important. It is required that the photon wavelength must be longer than the Schwarzschild radius of the lensing mass, and the source has to be smaller than the Fresnel length. Gould (1992) was the first to point out that this effect may be used to search for dark matter made of objects of $\sim 10^{-15} M_{\odot}$, as they might show up as anomalous spectral features in gamma-ray bursts at cosmological distance. Gould also invented the name 'femtolensing' to describe the phenomenon. The theory was farther elaborated by Stanek et al. (1993) and by Ulmer & Goodman (1994). Jaroszyński (1994) found that the diffrac-

tion effects can be present even when the photon wavelength is much smaller than the lens Schwarzschild radius, and in fact they limit the resolving power of caustics in Huchra's lens to $\sim 10^{-12}$ seconds of arc. No case of gravitational femtolensing has been detected as yet.

5. THE VALUES OF H_0 , Ω and Λ – GRAVITATIONAL MEGALENSING

The three most important cosmological parameters: H_0 , Ω , and Λ may be determined using gravitational lensing effects. When two well separated images of the source can be observed, and the source is variable, then the time delay between the variations as observed in the two images is proportional to the Hubble time, i.e. to H_0^{-1} (Kayser 1993, and references therein). The other parameters may also be estimated using the lens statistics (King 1993, and references therein). However, the classical method of estimating Ω and Λ is based on the redshift - angular diameter, or equivalently redshift - luminosity relation. Fundamentally this is the phenomenon of gravitational lensing by the universe as a whole, and it might be called megalensing. Currently, the best prospect to apply this classical method may be offered by supernovae of Type Ia (Colgate 1979, Branch & Tammann 1992, and references therein, Phillips 1993).

6. CONCLUSIONS

Strong gravitational macrolensing offers the most direct, and perhaps the most accurate determination of the mass of cosmological objects like galaxies and their clusters. Unfortunately, this method is applicable only to the objects with near critical column mass density. The weak gravitational macrolensing can be applied in more general, lower density conditions, but it is also less direct and hence less reliable. In some cases it is possible to measure directly the column mass density within the beam towards the images. Gravitational macrolensing can be used (and it is used) to establish the presence of dark matter of some kind, though so far it does not distinguish between the MACHOs and the WIMPS.

Gravitational microlensing (and femtolensing) can provide the most direct determination of the presence of MACHOs in a very large range of masses, from $10^{-15} M_\odot$ to $10^6 M_\odot$ (Nemiroff 1993, and references therein), but so far there is no definite evidence for or against MACHOs in any mass range. However, the recent successes of the MACHO and OGLE teams in detecting microlensing within our galaxy suggest that genuine MACHOs will be detected within a few years.

It is possible that supernovae Type Ia will allow the determination of Ω and Λ using the classical redshift - luminosity relations, which are related to gravitational lensing by all matter within the beam of radiation - gravitational megalensing. The Hubble constant may be measured, at least in principle. with the time delay effect.

Clearly, gravitational lensing is not the only way to study cosmology and to search for dark matter. However, it is one of the most useful and versatile approaches, and in some cases (mass determination) it is the most reliable.

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